



Deep Feedforwards Networks

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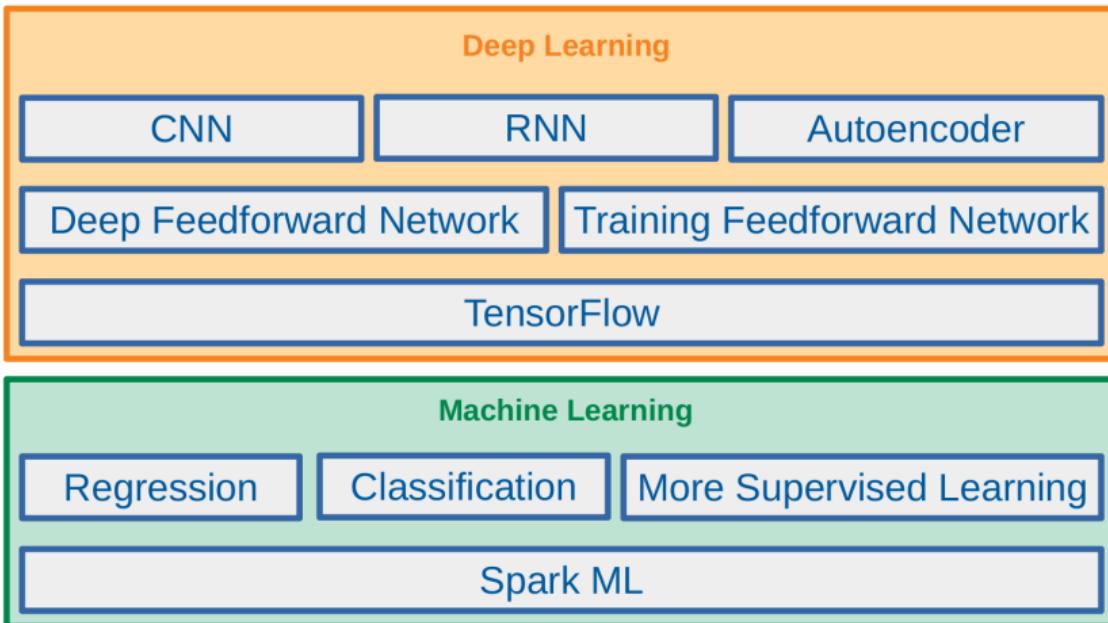


The Course Web Page

<https://id2223kth.github.io>

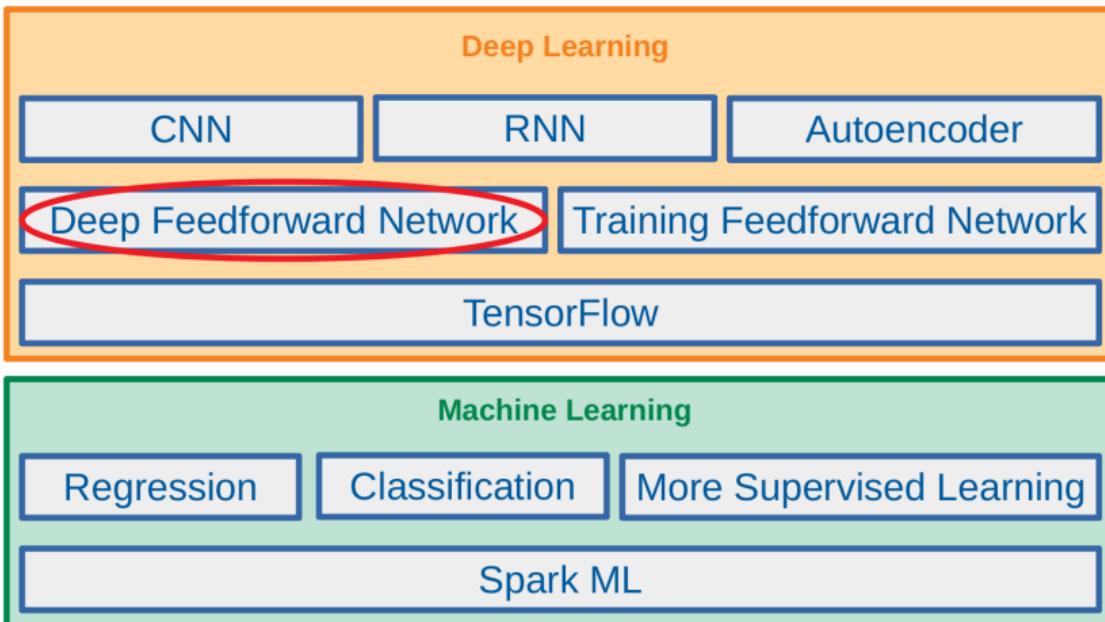


Where Are We?





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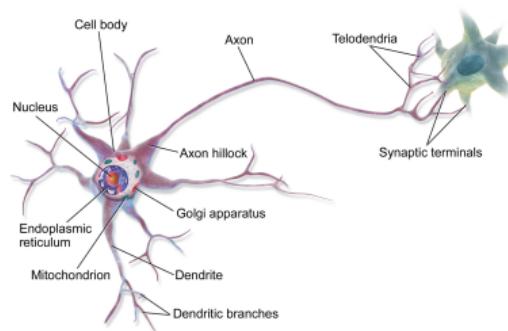
► Nature has inspired many of our **inventions**

- Birds inspired us to fly
- Burdock plants inspired velcro
- Etc.



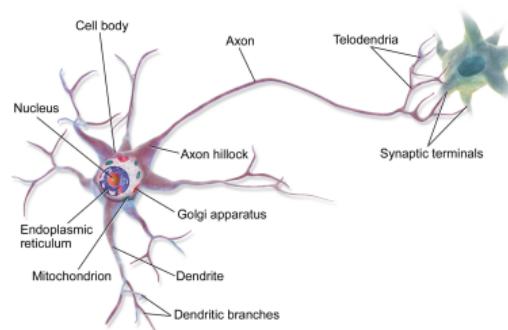
Biological Neurons (1/2)

- ▶ Brain architecture has inspired artificial neural networks.



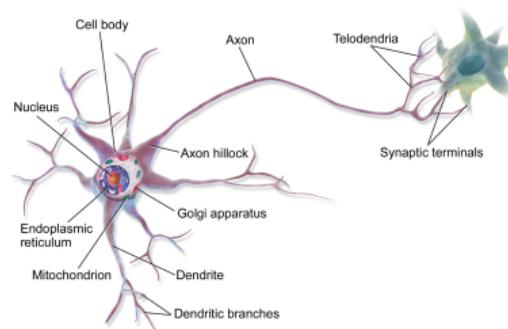
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- ▶ Brain architecture has inspired artificial neural networks.
- ▶ A biological neuron is composed of
 - Cell body, many dendrites (branching extensions), one axon (long extension), synapses



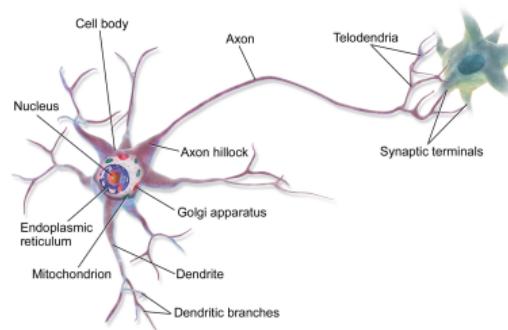
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- ▶ Biological neurons receive signals from other neurons via these synapses.



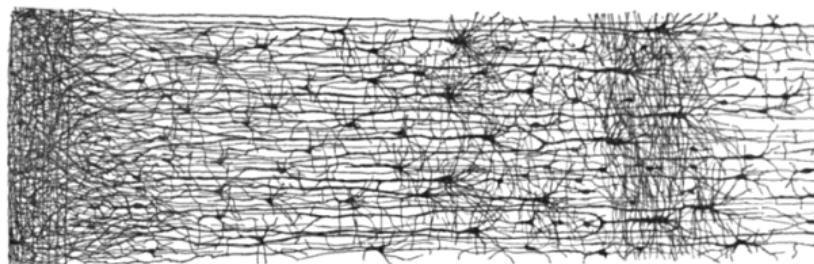
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- ▶ Brain architecture has inspired artificial neural networks.
- ▶ A biological neuron is composed of
 - Cell body, many dendrites (branching extensions), one axon (long extension), synapses
- ▶ Biological neurons receive signals from other neurons via these synapses.
- ▶ When a neuron receives a sufficient number of signals within a few milliseconds, it fires its own signals.



Biological Neurons (2/2)

- ▶ Biological neurons are organized in a vast **network of billions of neurons**.
- ▶ Each neuron typically is **connected to thousands of other neurons**.



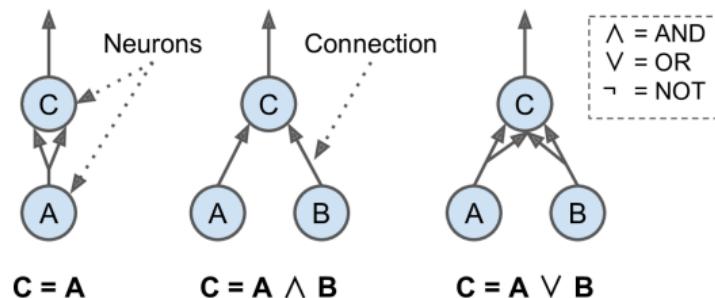


A Simple Artificial Neural Network

- ▶ One or more **binary inputs** and **one binary output**
- ▶ Activates its **output** when more than a **certain number of its inputs** are active.

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[A. Geron, O'Reilly Media, 2017]



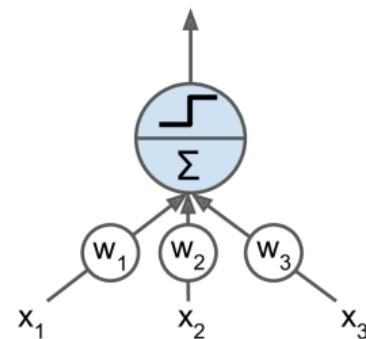
The Linear Threshold Unit (LTU)

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The Linear Threshold Unit (LTU)

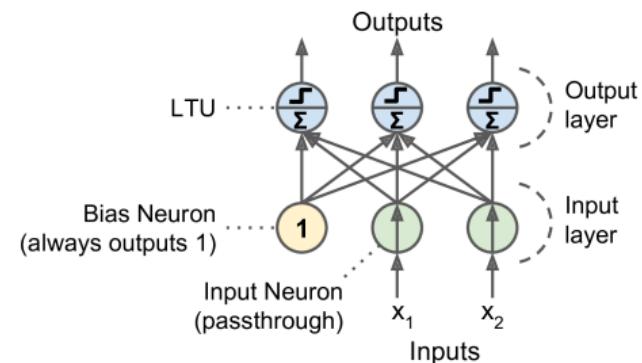
- ▶ Inputs of a LTU are **numbers** (not binary).
- ▶ Each **input connection** is associated with a **weight**.
- ▶ Computes a **weighted sum of its inputs** and applies a **step function** to that **sum**.

- ▶ $z = w_1x_1 + w_2x_2 + \dots + w_nx_n = \mathbf{w}^T\mathbf{x}$
- ▶ $\hat{y} = \text{step}(z) = \text{step}(\mathbf{w}^T\mathbf{x})$



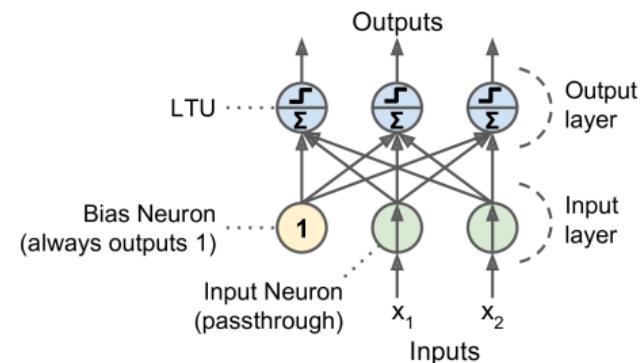
The Perceptron

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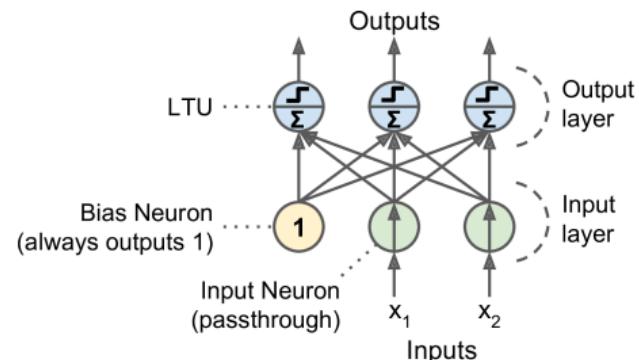
The Perceptron

- ▶ The **perceptron** is a **single layer** of LTUs.
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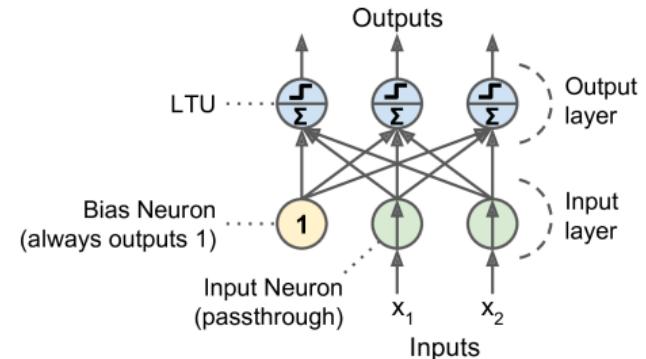
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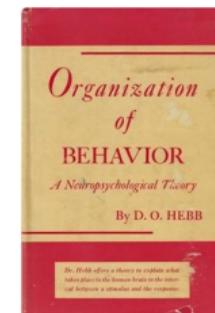
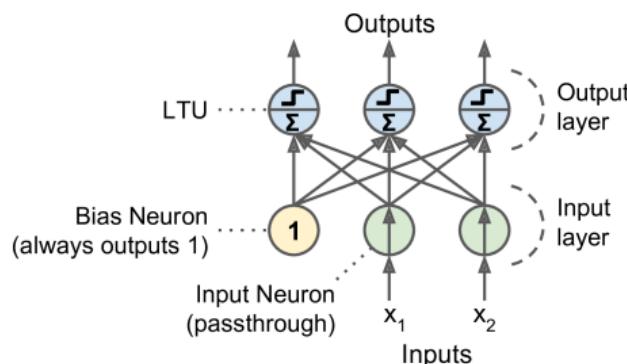
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- ▶ The **input neurons** output whatever **input** they are fed.
- ▶ A **bias neuron**, which just **outputs 1** all the time.
- ▶ If we use **logistic function (sigmoid)** instead of a **step** function, it computes a **continuous** output.



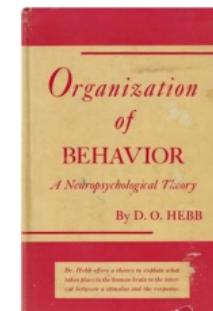
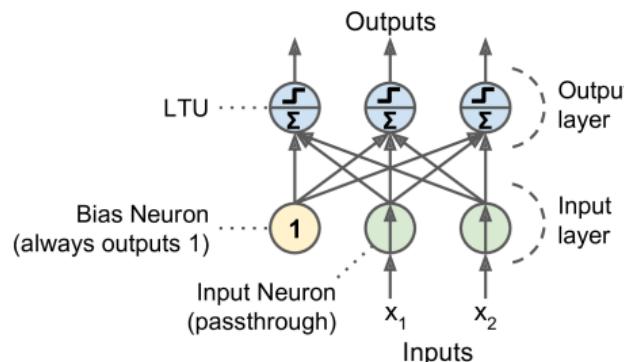
How is a Perceptron Trained? (1/2)

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How is a Perceptron Trained? (1/2)

- ▶ The **Perceptron training algorithm** is inspired by **Hebb's rule**.
- ▶ When a **biological neuron** often **triggers another neuron**, the **connection** between these two neurons grows **stronger**.





How is a Perceptron Trained? (2/2)

- ▶ Feed **one training instance x** to each neuron j at a time and make its **prediction \hat{y}** .
- ▶ Update the **connection weights**.

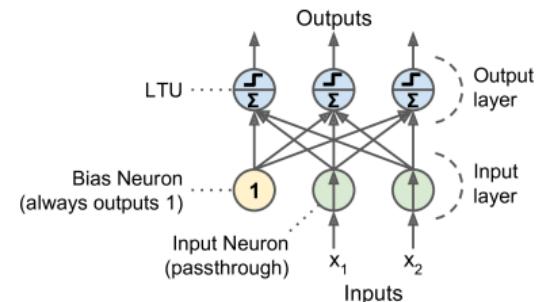
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$$J(\mathbf{w}_j) = \text{cross_entropy}(y_j, \hat{y}_j)$$

$$\mathbf{w}_{i,j}^{(\text{next})} = \mathbf{w}_{i,j} - \eta \frac{\partial J(\mathbf{w}_j)}{\mathbf{w}_i}$$



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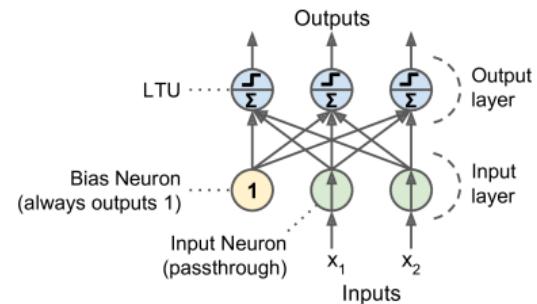
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- ▶ $w_{i,j}$: the weight between neurons i and j .
- ▶ x_i : the i th input value.
- ▶ \hat{y}_j : the j th predicted output value.
- ▶ y_j : the j th true output value.
- ▶ η : the learning rate.





Perceptron in TensorFlow



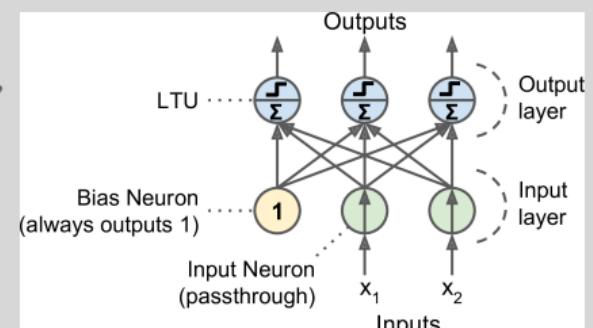
Perceptron in TensorFlow - First Implementation (1/3)

- ▶ `n_neurons`: number of neurons in a layer.
- ▶ `n_features`: number of features.

```
n_neurons = 3
n_features = 2

# placeholder
X = tf.placeholder(tf.float32, shape=(None, n_features),
                   name="X")
y_true = tf.placeholder(tf.int64, shape=(None),
                       name="y")

# variables
W = tf.get_variable("weights", dtype=tf.float32,
                     initializer=tf.zeros((n_features, n_neurons)))
b = tf.get_variable("bias", dtype=tf.float32,
                     initializer=tf.zeros((n_neurons)))
```





Perceptron in TensorFlow - First Implementation (2/3)

$$\hat{y}_j = \sigma(\mathbf{w}_j^T \mathbf{x} + b)$$

```
# make the network
z = tf.matmul(X, W) + b
y_hat = tf.nn.sigmoid(z)
```



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$$J(\mathbf{w}_j) = \text{cross_entropy}(y_j, \hat{y}_j) = - \sum_i^m y_j^{(i)} \log(\hat{y}_j^{(i)})$$

```
# define the cost
cross_entropy = -tf.reduce_sum(y_true * tf.log(y_hat), axis=1)
cost = tf.reduce_mean(cross_entropy)
```



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```
# train the model
# 1. compute the gradient of cost with respect to W and b
# 2. update the weights and bias
learning_rate = 0.1
new_W = W.assign(W - learning_rate * tf.gradients(xs=W, ys=cost))
new_b = b.assign(b - learning_rate * tf.gradients(xs=b, ys=cost))
```



Perceptron in TensorFlow - First Implementation (3/3)

- ▶ Execute the network.

```
# execute the model
init = tf.global_variables_initializer()

n_epochs = 100
with tf.Session() as sess:
    init.run()
    for epoch in range(n_epochs):
        sess.run([new_W, new_b, cost], feed_dict={X: training_X, y_true: training_y})
```



Perceptron in TensorFlow - Second Implementation (1/2)

$$\hat{y}_j = \sigma(\mathbf{w}_j^T \mathbf{x} + b)$$

```
# make the network
z = tf.matmul(X, W) + b
y_hat = tf.nn.sigmoid(z)
```



Perceptron in TensorFlow - Second Implementation (1/2)

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```

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```
# define the cost
cross_entropy = tf.nn.sigmoid_cross_entropy_with_logits(z, y_true)
cost = tf.reduce_mean(cross_entropy)
```



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```
# train the model
learning_rate = 0.1
optimizer = tf.train.GradientDescentOptimizer(learning_rate)
training_op = optimizer.minimize(cost)
```



Perceptron in TensorFlow - Second Implementation (2/2)

- ▶ Execute the network.

```
# execute the model
init = tf.global_variables_initializer()

n_epochs = 100
with tf.Session() as sess:
    init.run()
    for epoch in range(n_epochs):
        sess.run(training_op, feed_dict={X: training_X, y_true: training_y})
```



Perceptron in Keras

- ▶ Build and execute the network.

```
n_neurons = 10
y_hat = tf.keras.Sequential([layers.Dense(n_neurons, activation="sigmoid")])

y_hat.compile(optimizer=tf.train.GradientDescentOptimizer(0.001), loss="binary_crossentropy",
              metrics=["accuracy"])

n_epochs = 100
y_hat.fit(training_X, training_y, epochs=n_epochs)
```



Multi-Layer Perceptron (MLP)



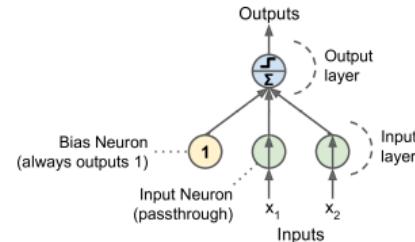
Perceptron Weakness (1/2)

- ▶ Incapable of solving some **trivial problems**, e.g., **XOR** classification problem. **Why?**

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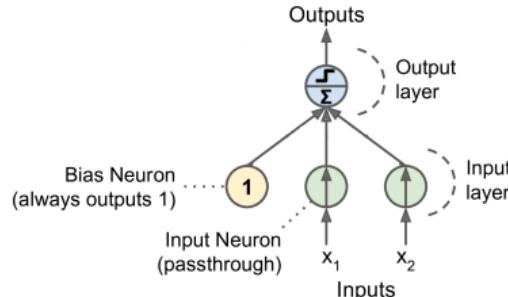
- Incapable of solving some **trivial problems**, e.g., **XOR** classification problem. **Why?**

A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0



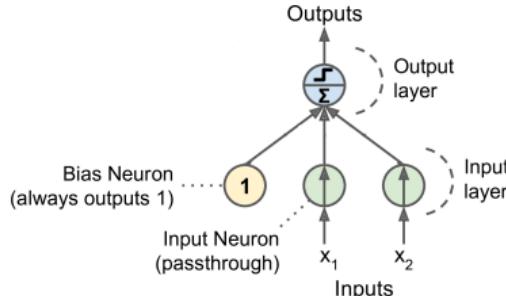
$$\mathbf{x} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 1 & 0 \\ 1 & 1 \end{bmatrix} \quad \mathbf{y} = \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix}$$

Perceptron Weakness (2/2)



$$\mathbf{x} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 1 & 0 \\ 1 & 1 \end{bmatrix} \quad \mathbf{y} = \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix} \quad \hat{\mathbf{y}} = \text{step}(z), z = w_1x_1 + w_2x_2 + b$$
$$J(\mathbf{w}) = \frac{1}{4} \sum_{\mathbf{x} \in \mathcal{X}} (\hat{\mathbf{y}}(\mathbf{x}) - \mathbf{y}(\mathbf{x}))$$

Perceptron Weakness (2/2)

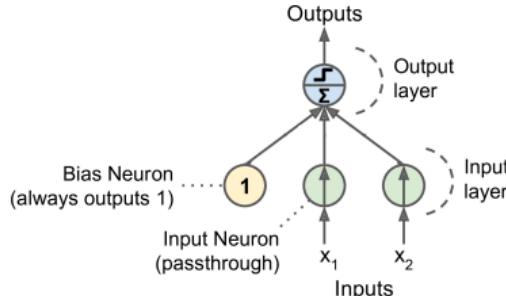


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- If we minimize $J(\mathbf{w})$, we obtain $w_1 = 0$, $w_2 = 0$, and $b = \frac{1}{2}$.
- But, the model outputs 0.5 everywhere.



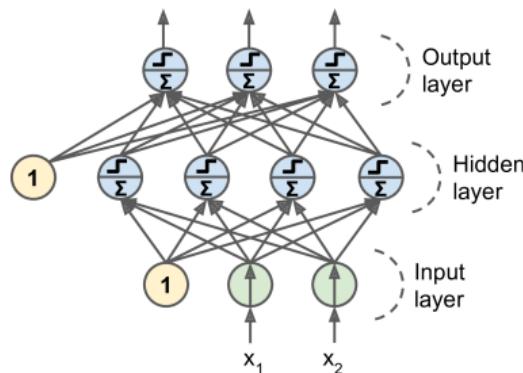
Multi-Layer Perceptron (MLP)

- ▶ The **limitations** of Perceptrons can be eliminated by **stacking multiple Perceptrons**.
- ▶ The resulting network is called a **Multi-Layer Perceptron (MLP)** or **deep feedforward neural network**.

Feedforward Neural Network Architecture

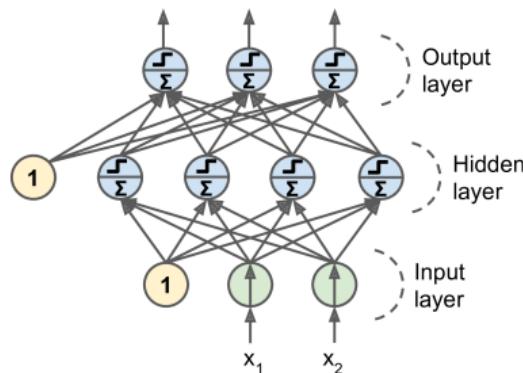
- ▶ A feedforward neural network is composed of:

- One **input layer**
- One or more **hidden layers**
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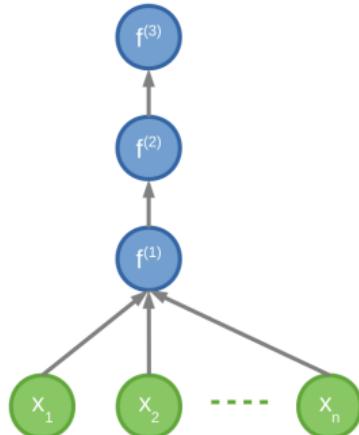
Feedforward Neural Network Architecture

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- ▶ Every layer except the output layer includes a **bias neuron** and is **fully connected** to the **next layer**.



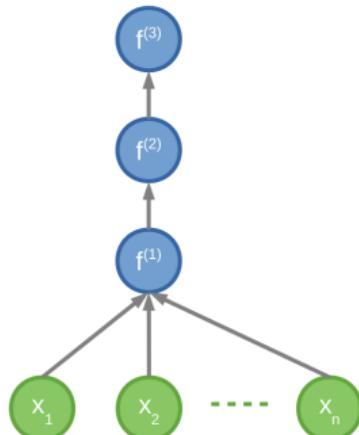
How Does it Work?

- ▶ The model is associated with a directed acyclic graph describing how the functions are composed together.



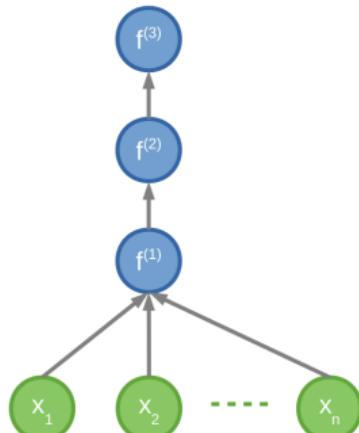
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- ▶ The model is associated with a directed acyclic graph describing how the functions are composed together.
- ▶ E.g., assume a network with just a single neuron in each layer.
- ▶ Also assume we have three functions $f^{(1)}$, $f^{(2)}$, and $f^{(3)}$ connected in a chain: $\hat{y} = f(x) = f^{(3)}(f^{(2)}(f^{(1)}(x)))$



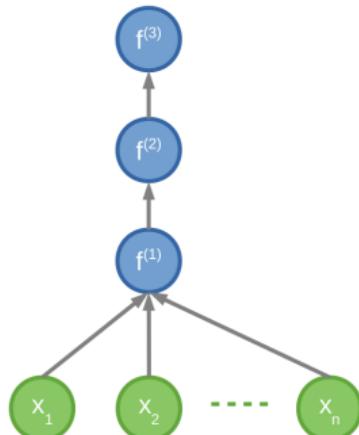
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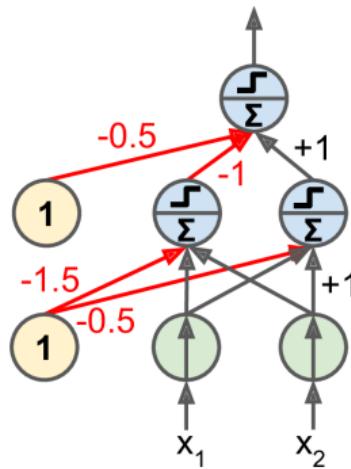


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- ▶ The length of the chain gives the depth of the model.

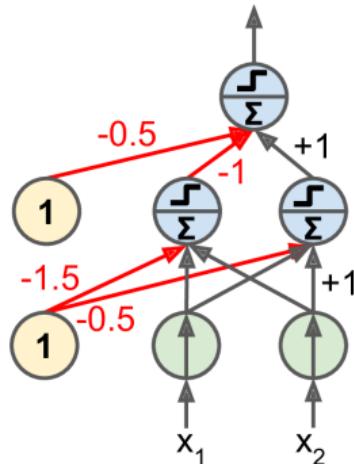


XOR with Feedforward Neural Network (1/3)



$$\mathbf{X} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 1 & 0 \\ 1 & 1 \end{bmatrix} \quad \mathbf{y} = \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix} \quad \mathbf{W_x} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \quad \mathbf{b_x} = \begin{bmatrix} -1.5 \\ -0.5 \end{bmatrix}$$

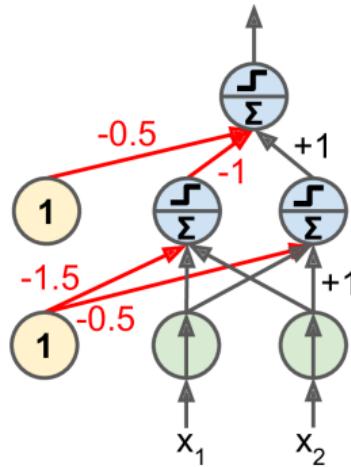
XOR with Feedforward Neural Network (2/3)



$$\text{out}_h = \mathbf{X} \mathbf{W}_x^T + \mathbf{b}_x = \begin{bmatrix} -1.5 & -0.5 \\ -0.5 & 0.5 \\ -0.5 & 0.5 \\ 0.5 & 1.5 \end{bmatrix} \quad h = \text{step}(\text{out}_h) = \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 0 & 1 \\ 1 & 1 \end{bmatrix}$$

$$\mathbf{w}_h = \begin{bmatrix} -1 \\ 1 \end{bmatrix} \quad \mathbf{b}_h = -0.5$$

XOR with Feedforward Neural Network (3/3)



$$\mathbf{out} = \mathbf{w}_h^T \mathbf{h} + \mathbf{b}_h = \begin{bmatrix} -0.5 \\ 0.5 \\ 0.5 \\ -0.5 \end{bmatrix} \quad \text{step}(\mathbf{out}) = \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix}$$



How to Learn Model Parameters W ?



Feedforward Neural Network - Cost Function

- ▶ We use the **cross-entropy** (minimizing the negative log-likelihood) between the training data y and the model's predictions \hat{y} as the **cost function**.

$$\text{cost}(y, \hat{y}) = - \sum_j y_j \log(\hat{y}_j)$$

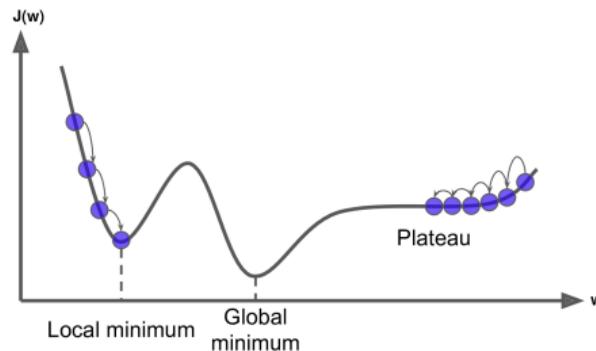


Gradient-Based Learning (1/2)

- ▶ The **most significant difference** between the **linear models** we have seen so far and **feedforward neural network**?

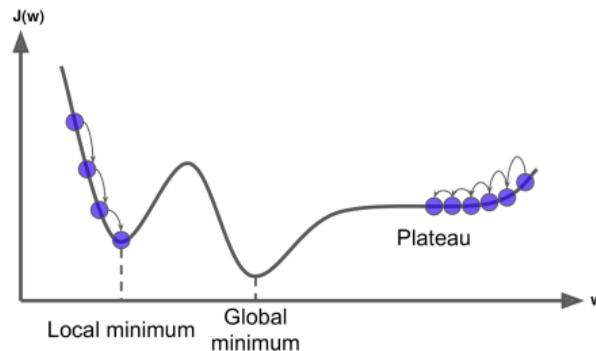
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- ▶ The **non-linearity** of a neural network causes its **cost functions** to become **non-convex**.
- ▶ Linear models, with **convex cost function**, **guarantee** to find **global minimum**.
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- ▶ Stochastic gradient descent applied to **non-convex cost functions** has no such convergence guarantee.



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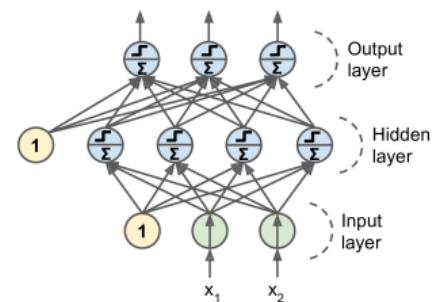


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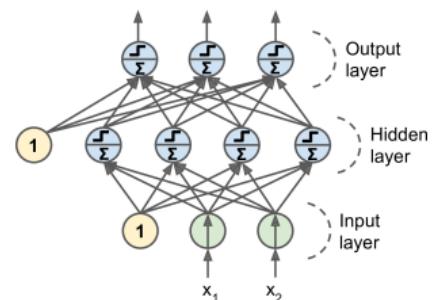
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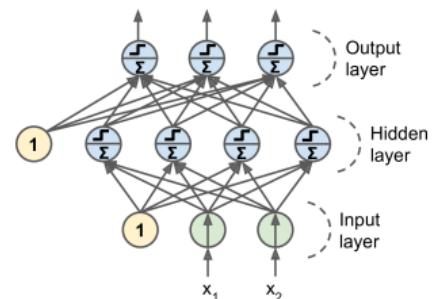
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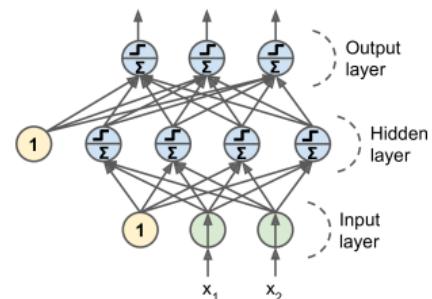
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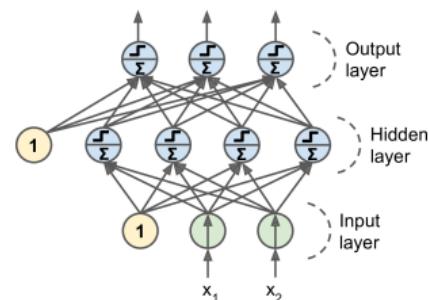
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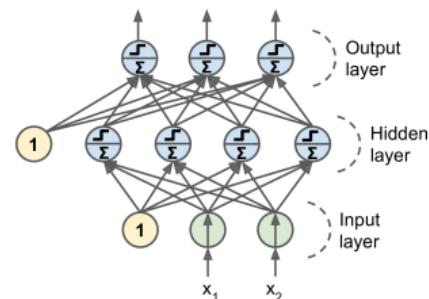
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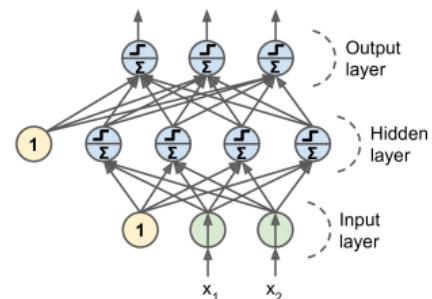
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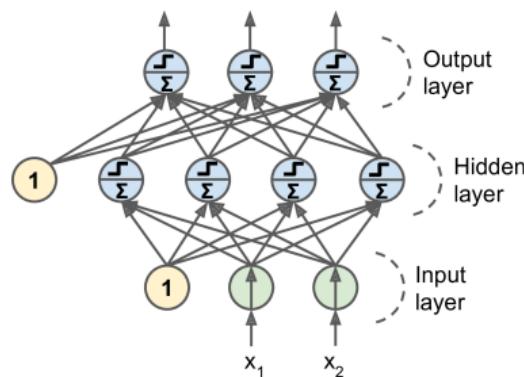
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- ▶ It's called the **backpropagation** training algorithm



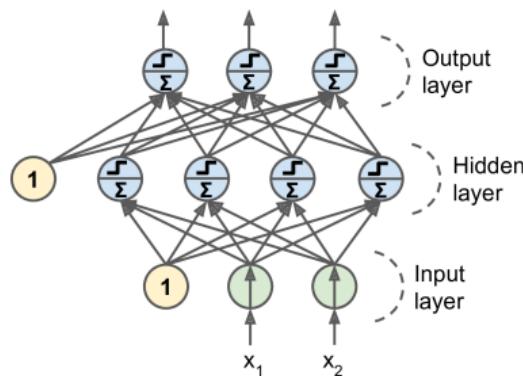
Output Unit (1/3)

- Linear units in neurons of the output layer.



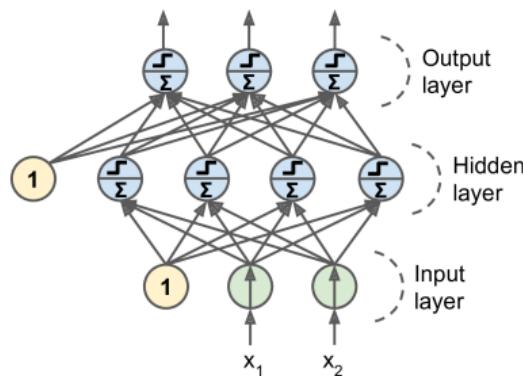
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- ▶ Linear units in neurons of the output layer.
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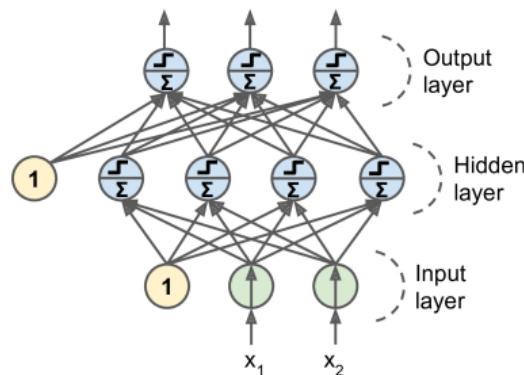
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- ▶ Minimizing the cross-entropy is then equivalent to minimizing the mean squared error.



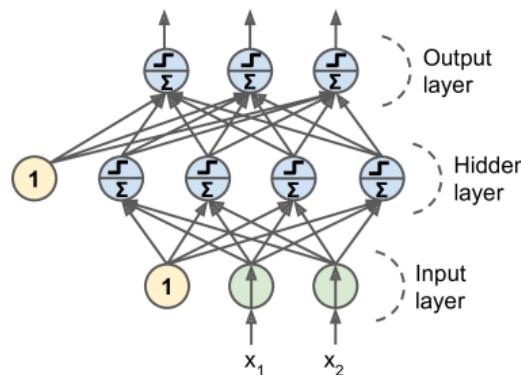
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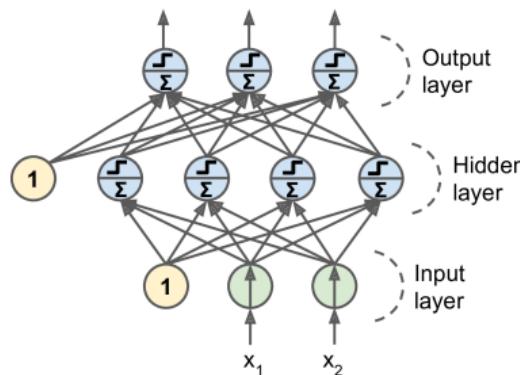
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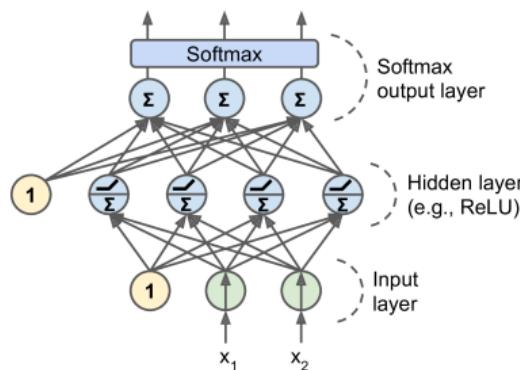
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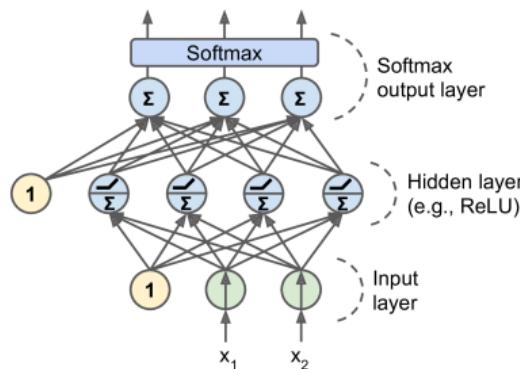
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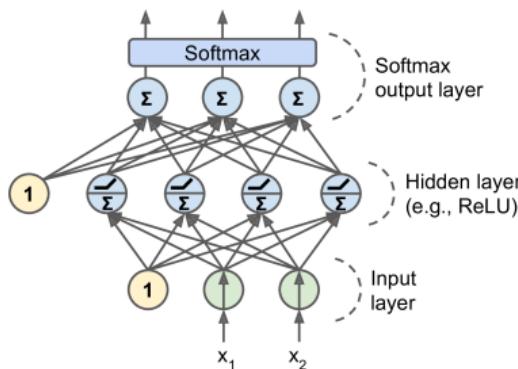
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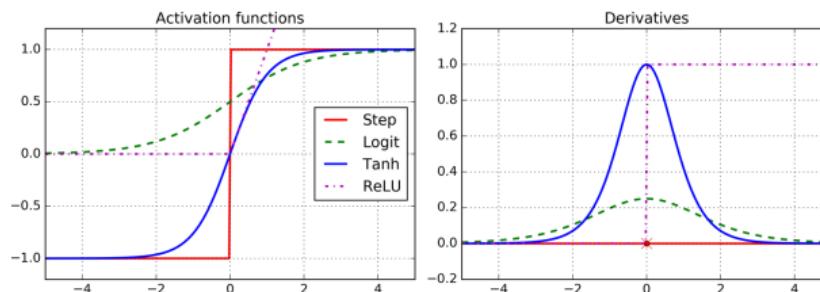


Hidden Units

- ▶ In order for the **backpropagation** algorithm to work properly, we need to **replace the step function** with **other activation functions**. **Why?**

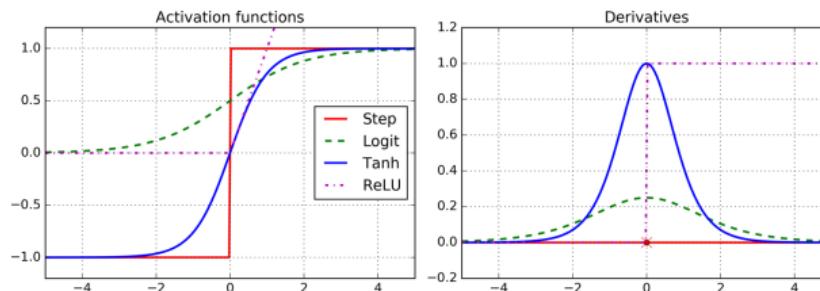
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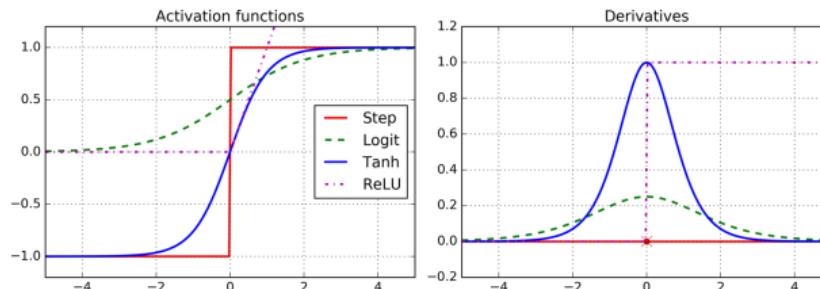
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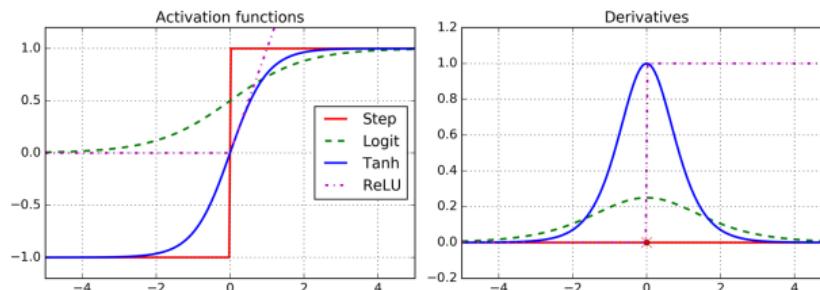
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 2. Hyperbolic tangent function: $\tanh(z) = 2\sigma(2z) - 1$
 3. Rectified linear units (ReLUs): $\text{ReLU}(z) = \max(0, z)$





Feedforward Network in TensorFlow

Feedforward in TensorFlow - First Implementation (1/3)

- ▶ `n_neurons_h`: number of neurons in the hidden layer.
- ▶ `n_neurons_out`: number of neurons in the output layer.
- ▶ `n_features`: number of features.

```
n_neurons_h = 4
n_neurons_out = 3
n_features = 2

# placeholder
X = tf.placeholder(tf.float32, shape=(None, n_features), name="X")
y_true = tf.placeholder(tf.int64, shape=(None), name="y")

# variables
W1 = tf.get_variable("weights1", dtype=tf.float32,
    initializer=tf.zeros((n_features, n_neurons_h)))
b1 = tf.get_variable("bias1", dtype=tf.float32, initializer=tf.zero((n_neurons_h)))

W2 = tf.get_variable("weights2", dtype=tf.float32,
    initializer=tf.zeros((n_features, n_neurons_out)))
b2 = tf.get_variable("bias2", dtype=tf.float32, initializer=tf.zero((n_neurons_out)))
```

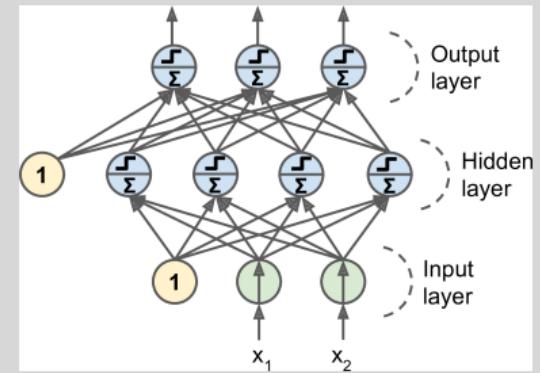
Feedforward in TensorFlow - First Implementation (2/3)

- Build the network.

```
# make the network
h = tf.nn.sigmoid(tf.matmul(X, W1) + b1)
z = tf.matmul(h, W2) + b2
y_hat = tf.nn.sigmoid(z)

# define the cost
cross_entropy =
    tf.nn.sigmoid_cross_entropy_with_logits(z, y_true)
cost = tf.reduce_mean(cross_entropy)

# train the model
learning_rate = 0.1
optimizer = tf.train.GradientDescentOptimizer(learning_rate)
training_op = optimizer.minimize(cost)
```





Feedforward in TensorFlow - First Implementation (3/3)

- ▶ Execute the network.

```
# execute the model
init = tf.global_variables_initializer()

n_epochs = 100
with tf.Session() as sess:
    init.run()
    for epoch in range(n_epochs):
        sess.run(training_op, feed_dict={X: training_X, y_true: training_y})
```

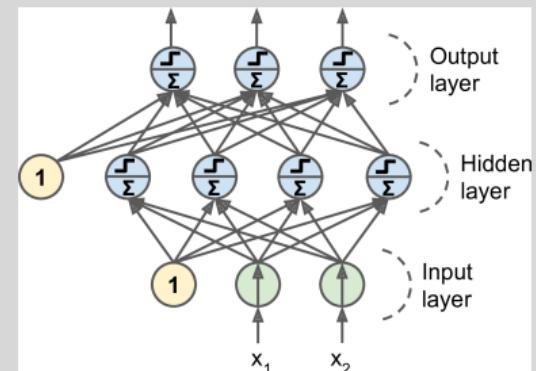
Feedforward in TensorFlow - Second Implementation

```
n_neurons_h = 4
n_neurons_out = 3
n_features = 2

# placeholder
X = tf.placeholder(tf.float32, shape=(None, n_features),
                   name="X")
y_true = tf.placeholder(tf.int64, shape=(None),
                       name="y")

# make the network
h = tf.layers.dense(X, n_neurons_h, name="hidden",
                    activation=tf.sigmoid)
z = tf.layers.dense(h, n_neurons_out, name="output")

# the rest as before
```





Feedforward in Keras

```
n_neurons_h = 4
n_neurons_out = 3
n_epochs = 100
learning_rate = 0.1

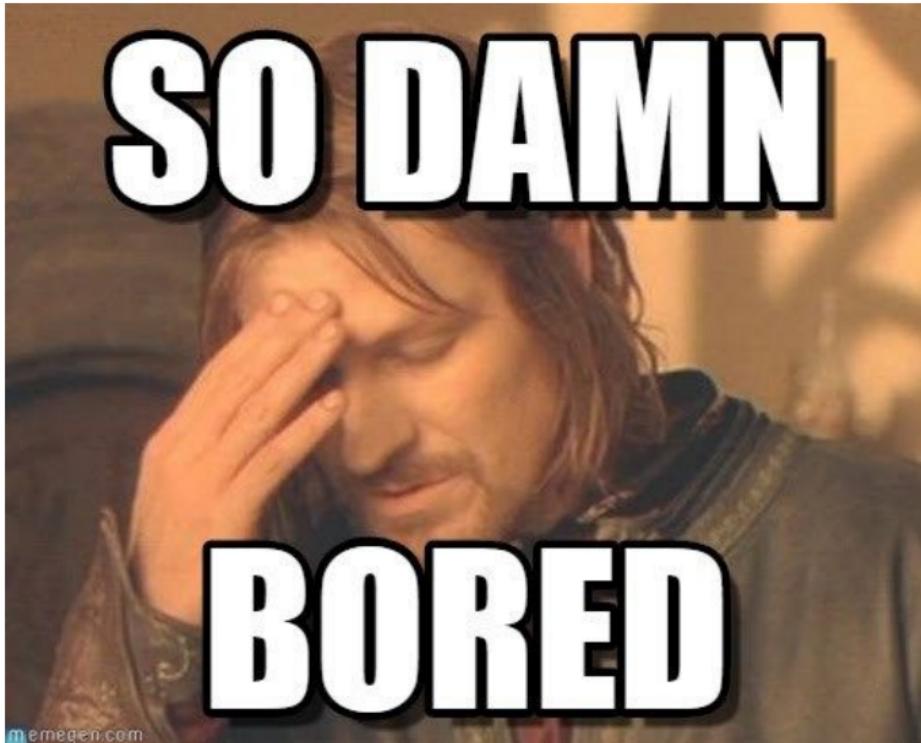
model = tf.keras.Sequential()
model.add(layers.Dense(n_neurons_h, activation="sigmoid"))
model.add(layers.Dense(n_neurons_out, activation="sigmoid"))

model.compile(optimizer=tf.train.GradientDescentOptimizer(learning_rate=.001),
              loss="binary_crossentropy", metrics=["accuracy"])

model.fit(training_X, training_y, epochs=n_epochs)
```



Dive into Backpropagation Algorithm



[<https://i.pinimg.com/originals/82/d9/2c/82d92c2c15c580c2b2fce65a83fe0b3f.jpg>]



Chain Rule of Calculus (1/2)

- ▶ Assume $x \in \mathbb{R}$, and two functions f and g , and also assume $y = g(x)$ and $z = f(y) = f(g(x))$.



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- ▶ Example:

$$z = f(y) = 5y^4 \text{ and } y = g(x) = x^3 + 7$$



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$$\frac{dz}{dy} = 20y^3 \text{ and } \frac{dy}{dx} = 3x^2$$



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$$\frac{dz}{dy} = 20y^3 \text{ and } \frac{dy}{dx} = 3x^2$$

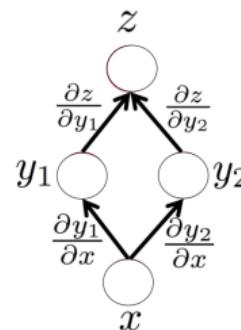
$$\frac{dz}{dx} = 20y^3 \times 3x^2 = 20(x^3 + 7) \times 3x^2$$

Chain Rule of Calculus (2/2)

- ▶ Two paths chain rule.

$z = f(y_1, y_2)$ where $y_1 = g(x)$ and $y_2 = h(x)$

$$\frac{\partial z}{\partial x} = \frac{\partial z}{\partial y_1} \frac{\partial y_1}{\partial x} + \frac{\partial z}{\partial y_2} \frac{\partial y_2}{\partial x}$$



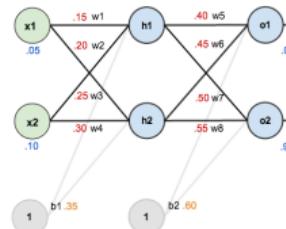


Backpropagation

- ▶ Backpropagation training algorithm for MLPs
- ▶ The algorithm repeats the following steps:
 1. Forward pass
 2. Backward pass

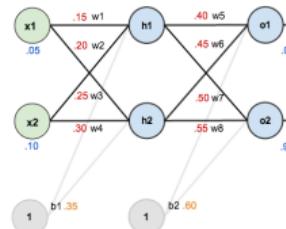
Backpropagation - Forward Pass

- ▶ Calculates outputs given input patterns.



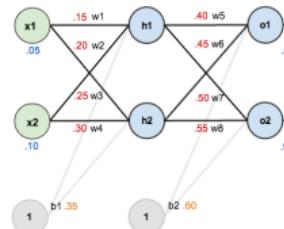
Backpropagation - Forward Pass

- ▶ Calculates outputs given input patterns.
- ▶ For each training instance



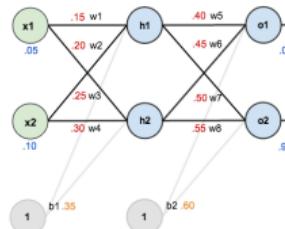
Backpropagation - Forward Pass

- ▶ Calculates outputs given input patterns.
- ▶ For each training instance
 - Feeds it to the network and computes the output of every neuron in each consecutive layer.



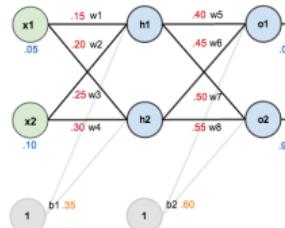
Backpropagation - Forward Pass

- ▶ Calculates outputs given input patterns.
- ▶ For each training instance
 - Feeds it to the network and computes the output of every neuron in each consecutive layer.
 - Measures the network's output error (i.e., the difference between the true and the predicted output of the network)



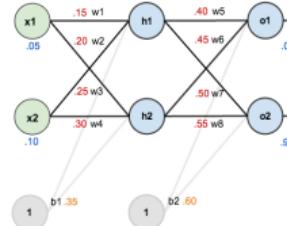
Backpropagation - Forward Pass

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- ▶ For each training instance
 - Feeds it to the network and computes the output of every neuron in each consecutive layer.
 - Measures the network's output error (i.e., the difference between the true and the predicted output of the network)
 - Computes how much each neuron in the last hidden layer contributed to each output neuron's error.



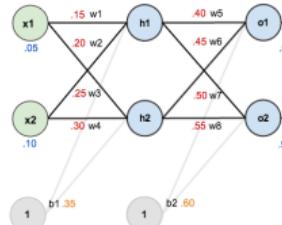
Backpropagation - Backward Pass

- ▶ Updates weights by calculating gradients.



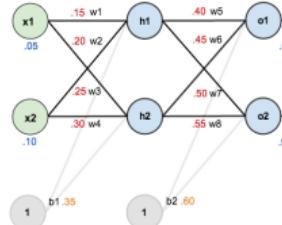
Backpropagation - Backward Pass

- ▶ Updates weights by calculating gradients.
- ▶ Measures how much of these error contributions came from each neuron in the previous hidden layer
 - Proceeds until the algorithm reaches the input layer.



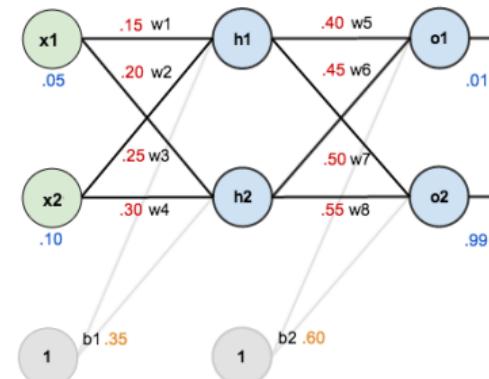
Backpropagation - Backward Pass

- ▶ Updates weights by calculating gradients.
- ▶ Measures how much of these error contributions came from each neuron in the previous hidden layer
 - Proceeds until the algorithm reaches the input layer.
- ▶ The last step is the gradient descent step on all the connection weights in the network, using the error gradients measured earlier.



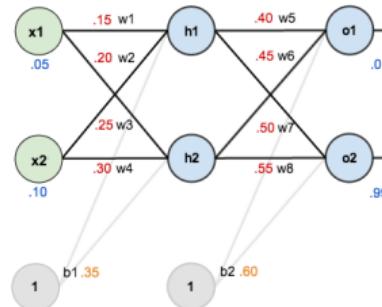
Backpropagation Example

- ▶ Two **inputs**, two **hidden**, and two **output** neurons.
- ▶ Bias in **hidden** and **output** neurons.
- ▶ Logistic activation in all the neurons.
- ▶ Squared error function as the cost function.



Backpropagation - Forward Pass (1/3)

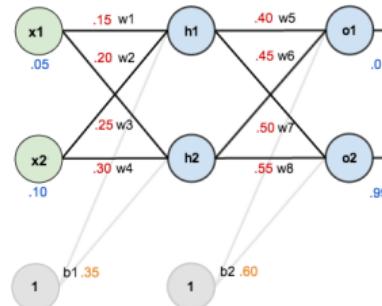
- ▶ Compute the **output** of the **hidden layer**



$$\text{net}_{h1} = w_1 x_1 + w_2 x_2 + b_1 = 0.15 \times 0.05 + 0.2 \times 0.1 + 0.35 = 0.3775$$

Backpropagation - Forward Pass (1/3)

- ▶ Compute the **output** of the **hidden layer**



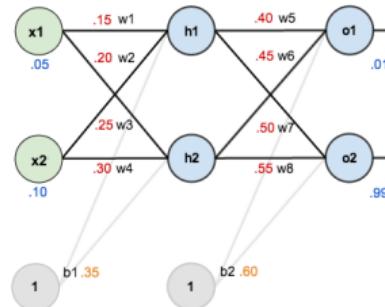
$$\text{net}_{h1} = w_1 x_1 + w_2 x_2 + b_1 = 0.15 \times 0.05 + 0.2 \times 0.1 + 0.35 = 0.3775$$

$$\text{out}_{h1} = \frac{1}{1 + e^{\text{net}_{h1}}} = \frac{1}{1 + e^{0.3775}} = 0.59327$$

$$\text{out}_{h2} = 0.59688$$

Backpropagation - Forward Pass (2/3)

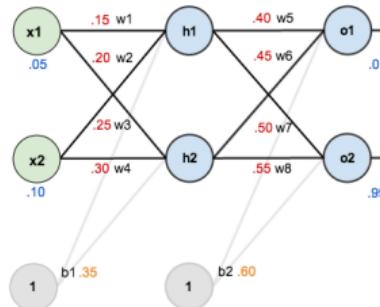
- ▶ Compute the **output** of the **output layer**



$$\text{net}_{o1} = w_5 \text{net}_{h1} + w_6 \text{net}_{h2} + b_2 = 0.4 \times 0.59327 + 0.45 \times 0.59688 + 0.6 = 1.1059$$

Backpropagation - Forward Pass (2/3)

- ▶ Compute the **output** of the **output layer**



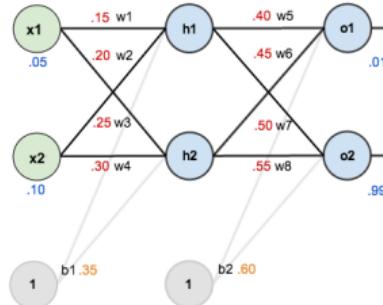
$$\text{net}_{o1} = w_5 \text{net}_{h1} + w_6 \text{net}_{h2} + b_2 = 0.4 \times 0.59327 + 0.45 \times 0.59688 + 0.6 = 1.1059$$

$$\text{out}_{o1} = \frac{1}{1 + e^{\text{net}_{o1}}} = \frac{1}{1 + e^{1.1059}} = 0.75136$$

$$\text{out}_{o2} = 0.77292$$

Backpropagation - Forward Pass (3/3)

- ▶ Calculate the **error** for each output



$$E_{o1} = \frac{1}{2}(\text{target}_{o1} - \text{output}_{o1})^2 = \frac{1}{2}(0.01 - 0.75136)^2 = 0.27481$$

$$E_{o2} = 0.02356$$

$$E_{\text{total}} = \sum \frac{1}{2}(\text{target} - \text{output})^2 = E_{o1} + E_{o2} = 0.27481 + 0.02356 = 0.29837$$

This class is boring...

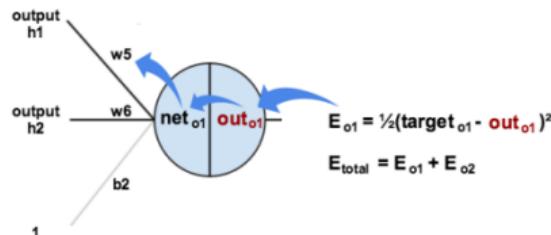


can we learn about dragons?

[<http://marimancusi.blogspot.com/2015/09/are-you-book-dragon.html>]

Backpropagation - Backward Pass - Output Layer (1/6)

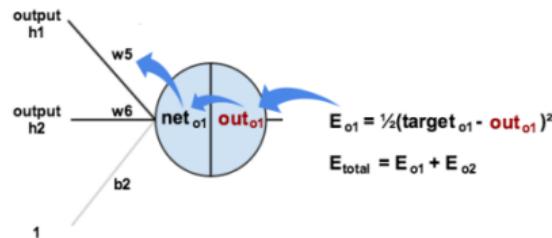
- ▶ Consider w_5
- ▶ We want to know how much a **change** in w_5 affects the **total error** ($\frac{\partial E_{\text{total}}}{\partial w_5}$)
- ▶ Applying the **chain rule**



$$\frac{\partial E_{\text{total}}}{\partial w_5} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} \times \frac{\partial \text{net}_{o1}}{\partial w_5}$$

Backpropagation - Backward Pass - Output Layer (2/6)

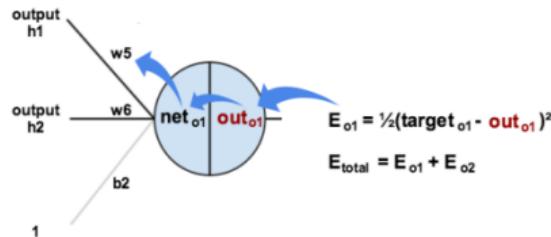
- ▶ First, how much does the total error change with respect to the output? ($\frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}}$)



$$\frac{\partial E_{\text{total}}}{\partial w_5} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} \times \frac{\partial \text{net}_{o1}}{\partial w_5}$$

Backpropagation - Backward Pass - Output Layer (2/6)

- First, how much does the total error change with respect to the output? ($\frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}}$)



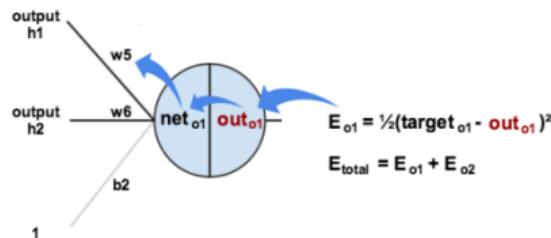
$$\frac{\partial E_{\text{total}}}{\partial w_5} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial net_{o1}} \times \frac{\partial net_{o1}}{\partial w_5}$$

$$E_{\text{total}} = \frac{1}{2}(\text{target}_{o1} - \text{out}_{o1})^2 + \frac{1}{2}(\text{target}_{o2} - \text{out}_{o2})^2$$

$$\frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}} = -2 \frac{1}{2}(\text{target}_{o1} - \text{out}_{o1}) = -(0.01 - 0.75136) = 0.74136$$

Backpropagation - Backward Pass - Output Layer (3/6)

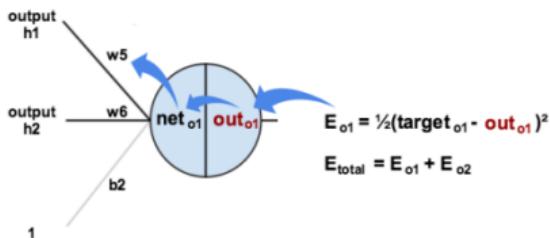
- ▶ Next, how much does the out_{o1} change with respect to its total input net_{o1} ?
 $(\frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}})$



$$\frac{\partial E_{\text{total}}}{\partial w_5} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} \times \frac{\partial \text{net}_{o1}}{\partial w_5}$$

Backpropagation - Backward Pass - Output Layer (3/6)

- ▶ Next, how much does the out_{o1} change with respect to its total input net_{o1} ?
 $(\frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}})$



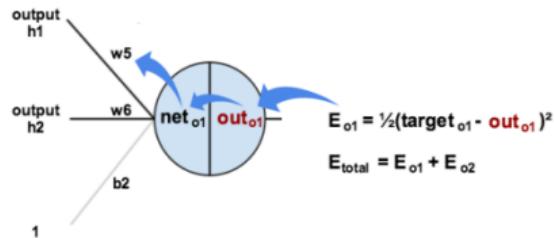
$$\frac{\partial E_{\text{total}}}{\partial w_5} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} \times \frac{\partial \text{net}_{o1}}{\partial w_5}$$

$$\text{out}_{o1} = \frac{1}{1 + e^{-\text{net}_{o1}}}$$

$$\frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} = \text{out}_{o1}(1 - \text{out}_{o1}) = 0.75136(1 - 0.75136) = 0.18681$$

Backpropagation - Backward Pass - Output Layer (4/6)

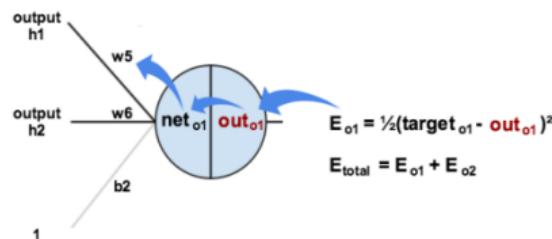
- ▶ Finally, how much does the total net_{o1} change with respect to w_5 ? ($\frac{\partial \text{net}_{o1}}{\partial w_5}$)



$$\frac{\partial E_{\text{total}}}{\partial w_5} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} \times \frac{\partial \text{net}_{o1}}{\partial w_5}$$

Backpropagation - Backward Pass - Output Layer (4/6)

- Finally, how much does the total net_{o1} change with respect to w_5 ? ($\frac{\partial \text{net}_{o1}}{\partial w_5}$)



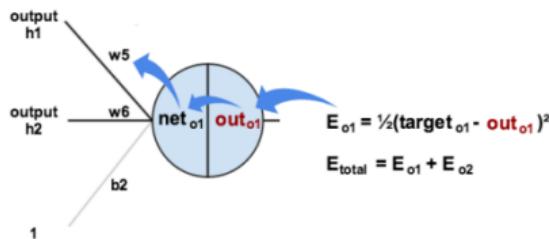
$$\frac{\partial E_{\text{total}}}{\partial w_5} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} \times \frac{\partial \text{net}_{o1}}{\partial w_5}$$

$$\text{net}_{o1} = w_5 \times \text{out}_{h1} + w_6 \times \text{out}_{h2} + b_2$$

$$\frac{\partial \text{net}_{o1}}{\partial w_5} = \text{out}_{h1} = 0.59327$$

Backpropagation - Backward Pass - Output Layer (5/6)

- ▶ Putting it all together:

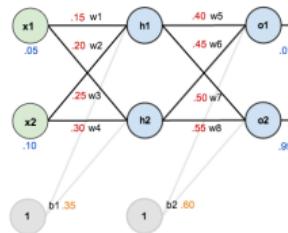


$$\frac{\partial E_{total}}{\partial w_5} = \frac{\partial E_{total}}{\partial out_{o1}} \times \frac{\partial out_{o1}}{\partial net_{o1}} \times \frac{\partial net_{o1}}{\partial w_5}$$

$$\frac{\partial E_{total}}{\partial w_5} = 0.74136 \times 0.18681 \times 0.59327 = 0.08216$$

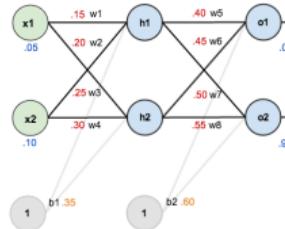
Backpropagation - Backward Pass - Output Layer (6/6)

- ▶ To decrease the error, we subtract this value from the **current weight**.



Backpropagation - Backward Pass - Output Layer (6/6)

- ▶ To decrease the error, we subtract this value from the current weight.
- ▶ We assume that the learning rate is $\eta = 0.5$.



$$w_5^{(\text{next})} = w_5 - \eta \times \frac{\partial E_{\text{total}}}{\partial w_5} = 0.4 - 0.5 \times 0.08216 = 0.35891$$

$$w_6^{(\text{next})} = 0.40866$$

$$w_7^{(\text{next})} = 0.5113$$

$$w_8^{(\text{next})} = 0.56137$$

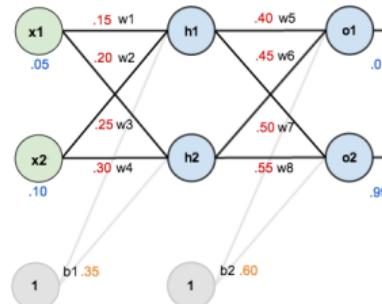


[<https://makeameme.org/meme/oooh-this>]

Backpropagation - Backward Pass - Hidden Layer (1/8)

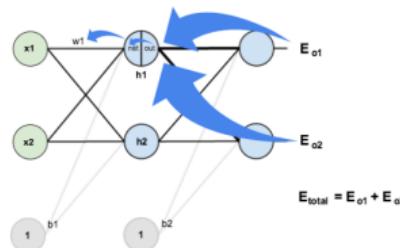
- ▶ Continue the **backwards pass** by calculating new values for w_1 , w_2 , w_3 , and w_4 .
- ▶ For w_1 we have:

$$\frac{\partial E_{\text{total}}}{\partial w_1} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{h1}} \times \frac{\partial \text{out}_{h1}}{\partial \text{net}_{h1}} \times \frac{\partial \text{net}_{h1}}{\partial w_1}$$



Backpropagation - Backward Pass - Hidden Layer (2/8)

- Here, the output of each hidden layer neuron contributes to the output of multiple output neurons.
- E.g., out_{h1} affects both out_{o1} and out_{o2} , so $\frac{\partial E_{total}}{\partial out_{h1}}$ needs to take into consideration its effect on the both output neurons.

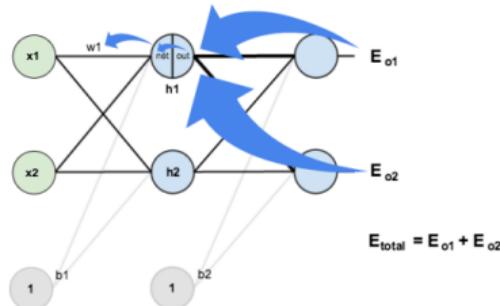


$$\frac{\partial E_{total}}{\partial w_1} = \frac{\partial E_{total}}{\partial out_{h1}} \times \frac{\partial out_{h1}}{\partial net_{h1}} \times \frac{\partial net_{h1}}{\partial w_1}$$

$$\frac{\partial E_{total}}{\partial out_{h1}} = \frac{\partial E_{o1}}{\partial out_{h1}} + \frac{\partial E_{o2}}{\partial out_{h1}}$$

Backpropagation - Backward Pass - Hidden Layer (3/8)

- ▶ Starting with $\frac{\partial E_{o1}}{\partial \text{out}_{h1}}$



$$\frac{\partial E_{\text{total}}}{\partial \text{out}_{h1}} = \frac{\partial E_{o1}}{\partial \text{out}_{h1}} + \frac{\partial E_{o2}}{\partial \text{out}_{h1}}$$

$$\frac{\partial E_{o1}}{\partial \text{out}_{h1}} = \frac{\partial E_{o1}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} \times \frac{\partial \text{net}_{o1}}{\partial \text{out}_{h1}}$$

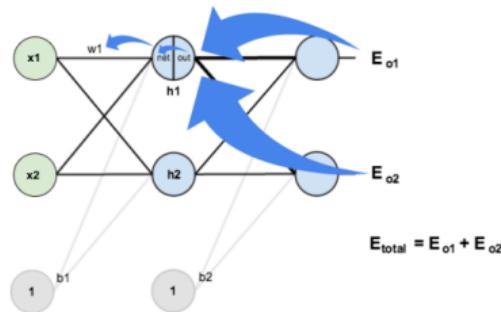
$$\frac{\partial E_{o1}}{\partial \text{out}_{o1}} = 0.74136, \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} = 0.18681$$

$$\text{net}_{o1} = w_5 \times \text{out}_{h1} + w_6 \times \text{out}_{h2} + b_2$$

$$\frac{\partial \text{net}_{o1}}{\partial \text{out}_{h1}} = w_5 = 0.40$$

Backpropagation - Backward Pass - Hidden Layer (4/8)

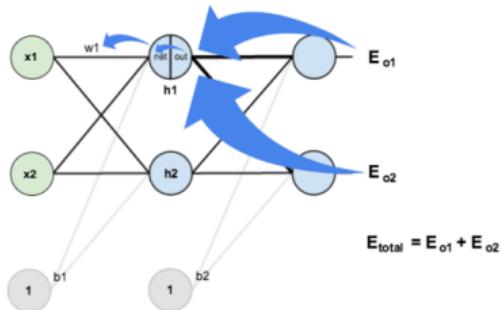
- ▶ Plugging them together.



$$\frac{\partial E_{o1}}{\partial \text{out}_{h1}} = \frac{\partial E_{o1}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} \times \frac{\partial \text{net}_{o1}}{\partial \text{out}_{h1}} = 0.74136 \times 0.18681 \times 0.40 = 0.0554$$
$$\frac{\partial E_{o2}}{\partial \text{out}_{h1}} = -0.01905$$

Backpropagation - Backward Pass - Hidden Layer (4/8)

- ▶ Plugging them together.



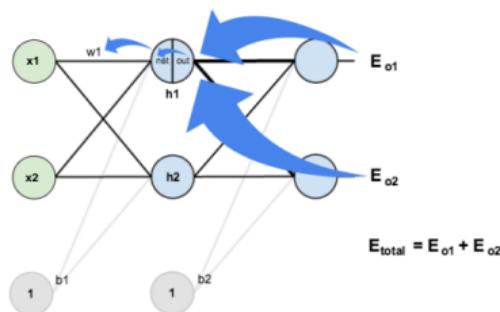
$$\frac{\partial E_{o1}}{\partial \text{out}_{h1}} = \frac{\partial E_{o1}}{\partial \text{out}_{o1}} \times \frac{\partial \text{out}_{o1}}{\partial \text{net}_{o1}} \times \frac{\partial \text{net}_{o1}}{\partial \text{out}_{h1}} = 0.74136 \times 0.18681 \times 0.40 = 0.0554$$

$$\frac{\partial E_{o2}}{\partial \text{out}_{h1}} = -0.01905$$

$$\frac{\partial E_{\text{total}}}{\partial \text{out}_{h1}} = \frac{\partial E_{o1}}{\partial \text{out}_{h1}} + \frac{\partial E_{o2}}{\partial \text{out}_{h1}} = 0.0554 + -0.01905 = 0.03635$$

Backpropagation - Backward Pass - Hidden Layer (5/8)

- Now we need to figure out $\frac{\partial \text{out}_{h1}}{\partial \text{net}_{h1}}$.



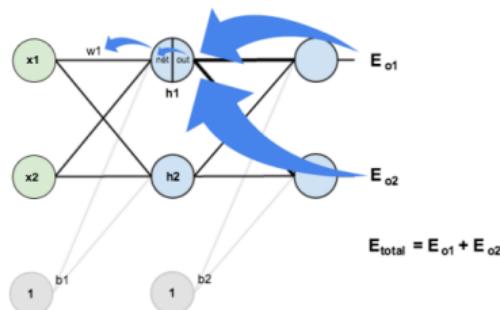
$$\frac{\partial E_{\text{total}}}{\partial w_1} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{h1}} \times \frac{\partial \text{out}_{h1}}{\partial \text{net}_{h1}} \times \frac{\partial \text{net}_{h1}}{\partial w_1}$$

$$\text{out}_{h1} = \frac{1}{1 + e^{-\text{net}_{h1}}}$$

$$\frac{\partial \text{out}_{h1}}{\partial \text{net}_{h1}} = \text{out}_{h1}(1 - \text{out}_{h1}) = 0.59327(1 - 0.59327) = 0.2413$$

Backpropagation - Backward Pass - Hidden Layer (6/8)

- And then $\frac{\partial \text{net}_{h1}}{\partial w_1}$.



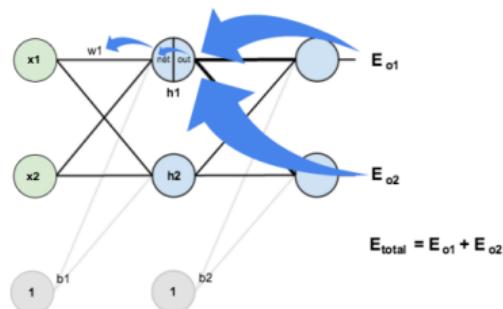
$$\frac{\partial E_{\text{total}}}{\partial w_1} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{h1}} \times \frac{\partial \text{out}_{h1}}{\partial \text{net}_{h1}} \times \frac{\partial \text{net}_{h1}}{\partial w_1}$$

$$\text{net}_{h1} = w_1 x_1 + w_2 x_2 + b_1$$

$$\frac{\partial \text{net}_{h1}}{\partial w_1} = x_1 = 0.05$$

Backpropagation - Backward Pass - Hidden Layer (7/8)

- ▶ Putting it all together.

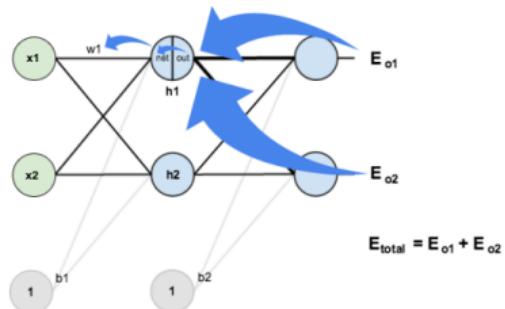


$$\frac{\partial E_{\text{total}}}{\partial w_1} = \frac{\partial E_{\text{total}}}{\partial \text{out}_{h1}} \times \frac{\partial \text{out}_{h1}}{\partial \text{net}_{h1}} \times \frac{\partial \text{net}_{h1}}{\partial w_1}$$

$$\frac{\partial E_{\text{total}}}{\partial w_1} = 0.03635 \times 0.2413 \times 0.05 = 0.00043$$

Backpropagation - Backward Pass - Hidden Layer (8/8)

- We can now update w_1 .
- Repeating this for w_2 , w_3 , and w_4 .



$$w_1^{(\text{next})} = w_1 - \eta \times \frac{\partial E_{\text{total}}}{\partial w_1} = 0.15 - 0.5 \times 0.00043 = 0.14978$$

$$w_2^{(\text{next})} = 0.19956$$

$$w_3^{(\text{next})} = 0.24975$$

$$w_4^{(\text{next})} = 0.2995$$



Summary



Summary

- ▶ LTU
- ▶ Perceptron
- ▶ Perceptron weakness
- ▶ MLP and feedforward neural network
- ▶ Gradient-based learning
- ▶ Backpropagation: forward pass and backward pass
- ▶ Output unit: linear, sigmoid, softmax
- ▶ Hidden units: sigmoid, tanh, relu



Reference

- ▶ Ian Goodfellow et al., Deep Learning (Ch. 6)
- ▶ Aurélien Géron, Hands-On Machine Learning (Ch. 10)



Questions?